High-Precision Reflectometry of Multilayer Coatings for Extreme Ultraviolet Lithography

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INTRODUCTION

For more than three decades, using shorter wavelengths and resolution enhancement techniques, optical lithography has enabled the semiconductor industry to deliver integrated circuits with ever increasing device density. It is anticipated that the introduction of excimer lasers in the ultraviolet spectral range will continue this trend to feature sizes below 100 nm. For further reduction of critical dimensions down to 25 nm, Extreme Ultraviolet Lithography (EUVL) is a promising technology. Currently efforts are made in Japan, Europe and the United States in order to develop the necessary components such as light sources, condenser systems, projection optics, and masks. Synchrotron radiation sources are important as a light source for the necessary metrology instruments. The Center for X-Ray Optics (CXRO) has built several dedicated beamlines to serve the needs for the development of EUVL. Applications include the calibration of detectors, interferometry, scatterometry and reflectometry. Of particular importance for precision manufacturing of multilayer coated EUVL components is the reflectometer installed at ALS beamline 6.3.2 [1]. Although the deposition of reflective multilayer coatings is a deterministic process, it requires continuous feedback on the result of individual coating runs. Most important is the feedback on the multilayer thickness distribution in addition to the verification of high peak reflectance. Based on the data obtained, magnetron sputter deposition is a robust method, which results in fast convergence of the coating prescription development process. For fast convergence the reflectometer must meet stringent optical and mechanical requirements, in addition to short turn-around times and high reliability of the data.

REFLECTIVE COATINGS FOR THE ENGINEERING TEST STAND

Figure 1 shows the optical layout of the Engineering Test Stand (ETS) [2], which is currently being built by the Virtual National Laboratory (VNL). All of the optical elements in the ETS are illuminated near normal incidence with the exception of the grazing incidence C2 mirror assembly and the C4 mirror. These grazing incidence mirrors are coated only with a single layer of ruthenium and provide broadband reflectance of 91% (at 8°) for C2 and 80% (at 16°) for C4. These values are achieved by a single reflection at the ruthenium-vacuum interface. In contrast, the normal-incidence elements achieve high reflectance by several reflections in a periodic molybdenum-silicon (Mo/Si) multilayer stack exploiting interference effects. Due to the resulting narrow reflectance peak the multilayer coatings require a precisely controlled bilayer thickness. For Mo/Si multilayers a typical FWHM bandwidth is 0.55 nm. In this case a wavelength matching of all components within ±0.04 nm is sufficient in order to achieve 96% of the ideal throughput. For high optical throughput it is also desirable to have peak reflectances of more than 65%. Since the condenser elements C1 and C3 are illuminated at different average angles in different locations, graded thickness multilayer coatings are required in order to maintain constant FWHM center wavelength for variable illumination angles.

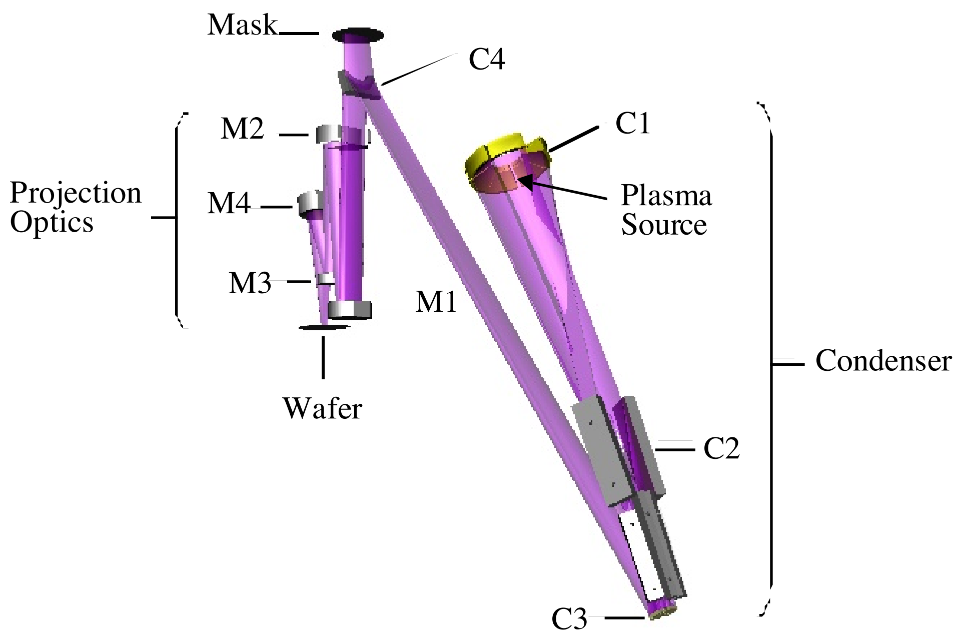

Figure 1. Layout of the ETS showing the EUV optical path from the laser-produced plasma source volume to the wafer stage through condenser optics, reticle stage, and projection optics.

For high-resolution lithographic printing multilayer coatings on EUVL projection optics must preserve the 0.25 nm (rms) figure of the mirror substrates. Considering the overall thickness of a multilayer coating of 300 nm, this means that the allowable relative error added is less than 0.1%. Specifications are very tight because purely geometrical distortion of the wavefront due to surface deformation is even enhanced by interference effects inside a non-uniform multilayer. On the other hand, multilayer non-uniformites typically have low spatial frequencies. Furthermore, tilting and focussing during the final alignment of the optical system can compensate for first and second order polynomial components of the non-uniformities. Therefore, the practical criterion for multilayer bilayer thickness uniformity is an allowable tolerance of 0.1 % peak-to-valley. As a consequence the absolute bilayer uniformity tolerance for wavelength near 13 nm is 0.01 nm peak-to-valley, which requires a measurement precision on the order of 0.002 nm.

REFLECTOMETRY AT ALS BEAMLINE 6.3.2

CXRO has built and is operating the reflectometer at beamline 6.3.2, which was especially designed for the characterization of multilayer coated EUVL optics. The main features of the beam delivered are spectral purity, small beam diameter, and high stability. The reflectometer features a detector arm with several detectors, including photodiodes, a channeltron and a CCD camera. Samples ranging from small test pieces to final ETS optics can be easily accommodated and manipulated with highly precise rotational and translational motions. Short pump-down times are achieved by a differentially pumped section, which separates the ultra-high vacuum of the monochromator from the vacuum conditions in the reflectometer. The interior of the reflectometer is easily accessible through an air-purged area by opening a large door on the side of the reflectometer tank. Beamline 6.3.2 provides unique features, which combine high precision with the flexibility to perform experiments in a variety of disciplines.

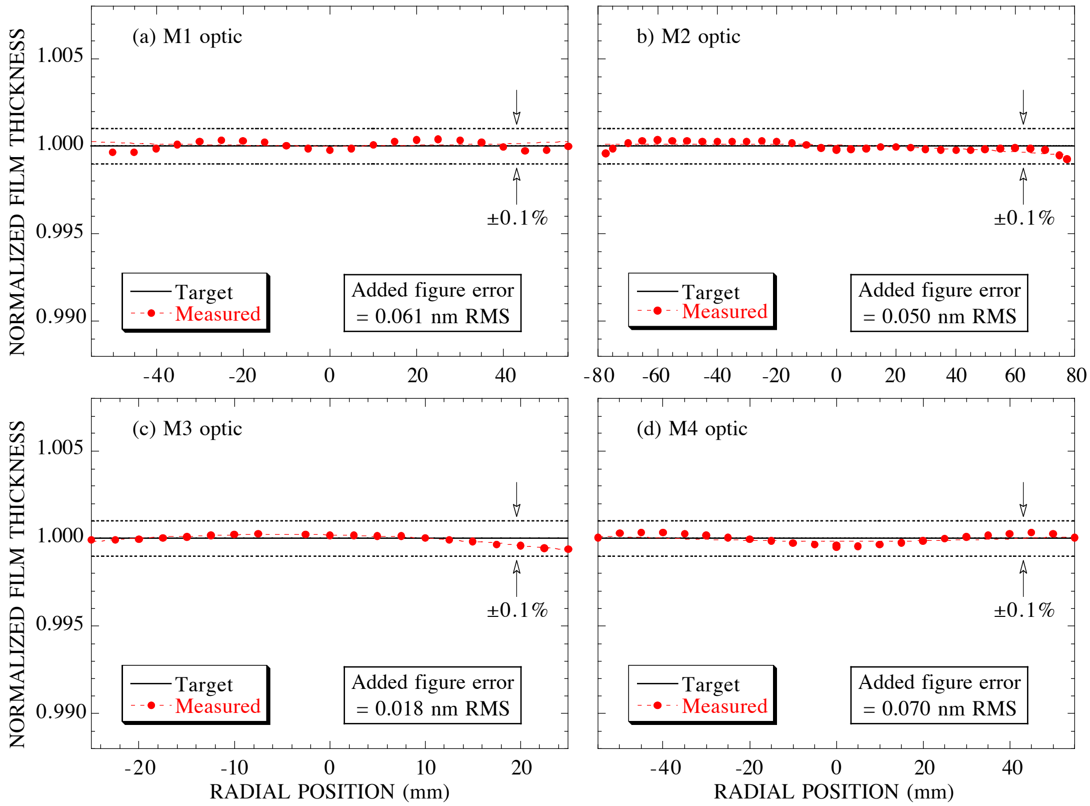

Figure 2. Normalized film thickness of the multilayer coating achieved on the ETS M1, M2, M3 and M4 projection optics. The figure error added by the deposition of the multilayer coatings is negligible for the performance of the overall optical system.

MEASUREMENT PRECISION

High-precision measurements of the reflective properties of multilayer coatings in the EUV spectral range require full control over the experimental geometry, spectral purity of the radiation source and suitable detectors. Synchrotron radiation facilities are ideally suited for precision reflectometry because they provide a well-collimated beam, high intensity, wide spectral range, and a clean environment. Beamline 6.3.2 at the ALS in Berkeley [1] and the PTB SX 700 beamline at BESSY in Berlin [3] utilize synchrotron-based reflectometers with the same level of precision. Other facilities utilizing laser produced plasma reflectometer also provide reflectivity data, but their precision may be limited by higher order contamination of the radiation, larger beam diameter and statistical noise introduced by a relatively low flux level. Until a few years ago there was a significant uncertainty about the reliability of reflectometry data. However, today with at least two synchrotron-based reflectometers delivering essentially identical results this uncertainty appears to be fully resolved. The reproducibility of results of measurements at ALS beamline 6.3.2 is 0.2% for reflectance and 0.002 nm for FWHM center wavelength.

APPLICATIONS

The reflectometer at ALS beamline 6.3.2 is supporting a variety of different activities within the EUVL program. The most important application is the support of the development of coating prescriptions for uniform or precisely graded, high reflectance multilayer coatings on ETS components such as optics and masks. A complete set of Mo/Si multilayer-coated components for the ETS meeting thickness distribution and reflectance specifications has been fabricated. Results on the multilayer uniformity and gradient control achieved are shown in figures 2 and 3. Another application is the feedback on reflective properties in the development of new multilayer coatings such as MoRu/Be. Also the assessment of temporal, thermal, chemical and radiation stability of multilayer reflective coatings is an important application.

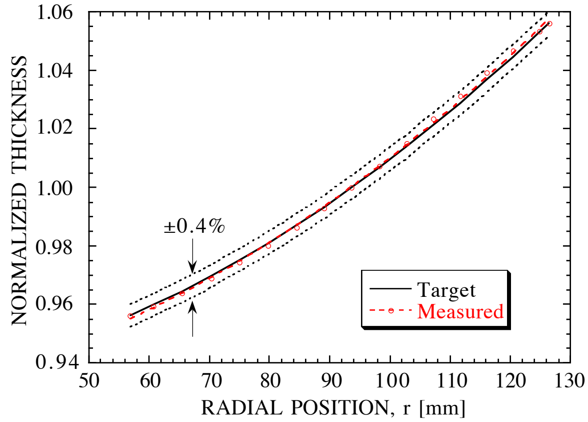

Figure 3. Normalized film thickness of the multilayer coating achieved on the ETS C1 condenser optics. The gradient achieved is sufficiently precise in order to ensure wavelength matching for all radial positions.

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